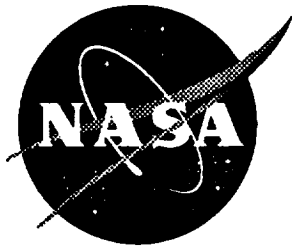


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Transport Delays Associated with the NASA Langley Flight Simulation Facility

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Summary

This paper describes the transport delays associated with flight simulation programs currently operating at the NASA Langley Research Center (LaRC). Formulas are presented for calculating a rough estimate of the transport delay for a particular simulation. Various simulation programs that used the Flight Simulation Facility (FSF) at LaRC, during the period of October 1993 to March 1994, were tested to determine the transport delays associated with the simulation program and any associated hardware. Several simulators were tested, including the Differential Maneuvering Simulator (DMS), the Visual Motion Simulator (VMS), and the Transport System Research Vehicle (TSRV).

Introduction

Research conducted at LaRC's FSF requires the simulation to match the real-world vehicle. Each simulation program contains math models that are used to describe the performance envelope of a particular vehicle. Since real-world delays are already included in the vehicles math model any additional delays due to the simulation would be considered superfluous. It is desirable to minimize these delays, defined as transport delays, as much as possible. Current studies show that acceptable transport delays are approximately 150 milliseconds (ms) for transport simulations^{1,2} and 100 ms for high performance aircraft³. This paper documents the transport delays associated with most of the research programs using the FSF.

Simulator Descriptions

A typical simulation requires several pieces of hardware and software, operating in conjunction, to generate the appropriate cues to the pilot. In general, necessary components include a cockpit, a real-time computer, a real-time control console, an image generator, cockpit instrumentation, and communications equipment. Fighter simulators may also require target projectors. Three of the major simulators located at the FSF are the Differential Maneuvering Simulator (DMS)⁴, the Visual Motion Simulator (VMS)⁵, and the Transport System Research Vehicle (TSRV)⁶. The DMS is used mostly for high performance and military aircraft research; the VMS is used for subsonic and hypersonic vehicles, high performance aircraft, and helicopter research, and the TSRV is used for subsonic transport related research. Each simulator uses the central facility concept of the FSF. In this concept, major simulation hardware components are shared among multiple simulations to increase productivity. The major components that are shared among the simulations are real-time control consoles, real-time computers, the Calligraphic/Raster Display System (CRDS), and the Computer-Generated Image (CGI) system.

Shared Resources

There are four real-time control consoles in the FSF. Each console can support an independent simulation. Prior to the startup of a simulation program the real-time operator schedules the equipment that will be necessary for a particular simulation. The scheduled hardware communicates with the real-time simulation program via a fiber optic Local Area Network (LAN) called the Advanced Real-Time Simulation System (ARTSS)⁷. Each simulation program can execute on one, or more, Central Processing Units (CPU) on one of two CONVEX super computers⁸. Since all of the simulations currently in production at the FSF execute on a single CPU this was the only CPU configuration tested. The cockpit instrumentation in the DMS, VMS, and TSRV is drawn by the CRDS onto Heads-Down-Display (HDD) monitors mounted in each cockpit. The CRDS is composed of three Terabit Eagle 1000 systems. Typically only one CRDS subsystem is required for a simulation. Each simulator uses one of two Evans and Sutherland CT6 eyepoints to render the out-the-window scene. In the DMS, the scene is projected onto the inside surface of a sphere with a resolution of approximately 13 arc minutes/pixel. The CGI scene is rendered for the VMS and the TSRV on XKD 8000 monitors, through collimating optics. The resolution of these displays is approximately 4 arc minutes/pixel.

Differential Maneuvering Simulator

The DMS consists of two 40 foot diameter spheres with a fighter cockpit at the center of each sphere. Each cockpit has a McFadden control loader, throttles, and various switches that the pilot can use to provide inputs to the simulation. The pilot receives information on the other aircraft's position via an image of a target projected onto the sphere wall. Each sphere's target is rendered with a Silicon Graphics Incorporated (SGI) 320 VGX system and is then projected onto the sphere using a monochrome General Electric (GE) light valve and a McDonnell Douglas mirror projection system. The resolution of the projected target is approximately 1024 TV lines. Each DMS cockpit uses the CRDS to drive three calligraphic monitors and one Heads-Up-Display (HUD) for cockpit instrumentation. The CGI image, for the external visual scene, is projected onto the sphere's surface with GE color light valves.

Visual Motion Simulator

The VMS is a generic cockpit mounted on a 6-degree-of-freedom motion base platform. The cockpit provides two McFadden control loaders; a left side-arm for the pilot and a center stick for the co-pilot. The co-pilot's seat has a collective mounted to it to allow for helicopter simulations. Throttles and other various switches are used to provide additional control inputs to the simulation program. The CRDS is used for displaying the cockpit's instrumentation onto six monitors. In addition, a CRDS display can be mixed with the CGI system to provide a HUD in the cockpit. The CGI system drives four XKD monitors to provide the out-the-window scenery.

Transport Systems Research Vehicle

The TSRV cockpit is a research cockpit configured as a modified research 737 cockpit. The cockpit uses McFadden side-arm control loaders for both the pilot and co-pilot. As in the other simulators, throttles and various switches provide additional control inputs to the simulation program. The CRDS provides cockpit instrumentation on all eight monitors in the TSRV cockpit. A HUD can also be displayed by mixing a CRDS display with the CGI system. The CGI system drives four XKD monitors to provide the out-the-window scenery.

Experimental Setup

The transport delay for each simulation real-time program was measured using a time based analysis technique. References 9 and 10 provide detailed explanations of the measurement setup. Each simulator uses a baseline program that is modified to provide the base control system for a particular vehicle. The baseline program for each simulator was modified to monitor a discrete switch at the input of an Analog-to-Digital Converter (ADC) for the control loader. The pitch axis was used on the DMS and the roll axis was used for the VMS and TSRV. By modifying the baseline program, these changes are available to each vehicle using the program. Each vehicle was then trimmed to a stable flight condition and the simulation program placed in the operate mode. Next the switch was toggled, and the time for the various hardware subsystems to respond to the input was measured with a logic analyzer.

Transport Delays

This test does not verify the fidelity of the simulation. Rather it is useful to determine if the math model and the simulation hardware is responding as quickly as possible to an input. Therefore, this test only measures the onset of a response. Most of the math models begin to respond within one frame of the input, therefore; most programs will have approximately the same transport delay. The transport delay due to the simulation implementation is a function of the simulation update rate. The inputs are read at the beginning of each frame. The program then processes these inputs to generate the next state information for the various math model subsystems and simulation output devices. The data for the CT6, SGI and the target servo is sent, asynchronously, to the respective devices as soon as the necessary information is generated. This usually occurs within 5 to 10 milliseconds (ms) from the beginning of the frame on the CONVEX, and depends mostly on the length of the vehicles math model code. The data for the CRDS is sent asynchronously at the beginning of the next frame so that any remaining equations can be calculated. Outputs to synchronous devices are generated at the end of a simulation frame. Cockpit Input/Output (I/O) is usually passed as synchronous data. The transport delays presented are averages based on 20 measurements. These averages give an estimate of the amount of time it takes for a particular system to begin responding to the pilot's input. Due to the highly asynchronous nature of the transmission paths to different pieces of equipment, these numbers are only accurate to within ± 5 ms. However, this does give an indication as to whether improvements should be made to the model or if an error has been introduced in the program.

DMS Transport Delays

The transport delays that were measured for the DMS were the delays associated with the CGI, SGI, and the CRDS. The time from the switch toggle to the completion of the first field of raster video of the CGI and the SGI was measured. Also, the time from the switch toggle to the completion of the calligraphic CRDS display was measured. The transport delay for the analog target generator servo was measured using a sinusoidal input rather than the discrete step generated by a switch. The sinusoidal input was patched into the pitch axis and was plotted against the servo output at various frequencies to determine the servo response. The following table shows the transport delays for simulation vehicles tested.

Program Name (Update Rate)	Switch to CGI Complete (ms)	Switch to CRDS Complete (ms)	Switch to SGI Complete (ms)
F-18 Baseline (31.25 Hz)	113	123	105
F-18 Baseline (62.5 Hz)	100	94	98
SUPFIT/TIGRES (31.25 Hz)	116	127	107
CAMS (31.25 Hz)	112	128	106
AGILE (40 Hz)	113	118	103
HANG (40 Hz)	113	118	103
HARV (40 Hz)	112	117	107
HAV2 (33 Hz)	113	123	105
HAIRRY (31.25 Hz)	115	121	106
F-16XL Baseline (62.5 Hz)	101	99	94

The transport delay for the target servo is shown below. The servo was tested at several frequencies to yield a steady state delay at those frequencies.

Frequency (Hz)	Transport Delay (ms)
0.3	37
0.5	40
0.7	44
1.0	47
1.5	50
2.0	70
2.5	80
3.0	95
5.0	100

VMS Transport Delays

The transport delays measured for the VMS were the delays associated with the CGI, and the CRDS. The following table shows the transport delay data for the respective jobs tested.

Program Name (Update Rate)	Switch to CT6 Complete (ms)	Switch to CRDS Complete (ms)
GHS (32 Hz)	144	159
HSCT (32 Hz)	139	156
PLS (32 Hz)	109	133

From the data above the PLS program measures about a frame faster than the GHS, and HSCT programs. Upon further investigation, it was discovered that the control laws for the GHS and HSCT vehicles do not begin to respond to inputs until more than 30 ms after an input is detected.

TSRV Transport Delays

The transport delays that were measured for the TSRV were the delays associated with the CGI, and the CRDS. The following table shows the transport delay data for the respective jobs tested.

Program Name (Update Rate)	Switch to CT6 Complete (ms)	Switch to CRDS Complete (ms)
CC - Baseline (32 Hz)	111	135
TEEM (32 Hz)	108	137
IIC (32 Hz)	113	137
CWIN (32 Hz)	111	135
HSS (32 Hz)	114	138
WCP (32 Hz)	107	135
WCP-DH (32 Hz)	108	133

Data Analysis

The transport delay measured for the various simulation components is usually a function of the update rate of the real-time simulation program and each subsystem. In general, the faster the real-time program and the different subsystems operate, the lower the overall transport delay. The theoretical average transport delay, for the CGI, CRDS and the SGI, can be calculated using the following equations:

$$\begin{aligned}td_{cgi} &\approx (0.5 \cdot h) + td_{prog} + td_{arts} + cgi \\td_{crds} &\approx (1.5 \cdot h) + td_{prog} + td_{arts} + pipe \cdot update \\td_{sgi} &\approx (0.5 \cdot h) + td_{prog} + td_{arts} + sgi \cdot (1.5 \cdot \text{ceil}(update/sgi) + 1)\end{aligned}$$

Where:

h = simulation step size (ms)

td_{prog} = time in program (ms)

td_{arts} = transmission time (ms)

cgi = 92 ms, the time required for the CGI to sample and render the image

$pipe$ = 5.5, the number of pipeline stages in the CRDS

$update$ = the update rate for the graphics program (ms)

sgi = 16.7 ms, the frame update on the SGI

$ceil(x)$ = smallest integer $\geq x$

In some systems, as the update rate is increased, other factors in the system become more prevalent and reduce the effectiveness of the system. For example, the CRDS can operate with display update rates up to 120 Hz. The theoretical transport delay of the CRDS should be approximately 5.5 times the update rate or 46 ms. If a 32 Hz simulation program were driving a CRDS operating at 120 Hz one would calculate an anticipated transport delay ≈ 103 ms. However, the measured transport delay was an average 19 ms longer (or ≈ 122 ms). This is caused by excessive collisions occurring on the CRDS I/O buses. At the very high update rates, the graphics pipeline uses a high percentage of the bus bandwidth. This leaves less time for communications data from the real-time simulation program to be transferred on the bus. The SGI system follows the theoretical equation fairly well, however, the update rate of the graphics program should be measured with the `swap_buffer` call commented out. This will reveal the actual refresh rate and the amount of idle time before the system redraws the screen. The SGI systems can suffer from the excessive delays due to the buses and CPU usage. The SGI's used for the target projectors are single CPU systems. Therefore, high update rates coupled with high graphics update rates can have deleterious effects. However, this phenomena was not noticed until the real-time update rate exceeded 160 Hz. The CGI times are very stable, since the system always updates at 50 Hz; therefore, the theoretical calculations agree very well with the measured times. The CGI behaved as the theoretical equation predicted throughout range of possible real-time update rates.

From the data above one can see that the faster the real-time simulation program update rate, the lower the transport delay. This is mostly due to the elimination of slack CPU time on the CONVEX. Since the CONVEX CPU's are very powerful, most real-time simulation programs execute within the first 5 ms of the real-time frame. By increasing the frame rate, through lowering the frame time, the amount of idle CPU time is greatly reduced. This is especially true for the CRDS transport delay since the program must wait an entire frame before the data is sent to the CRDS. This is because several variables to be displayed must be calculated at the beginning of the next frame before they are sent to the CRDS. Although the increase in frame rate reduces the transport delay, the benefits diminish as the frame rate is increased. For example, if the simulation program were to operate at 120 Hz the time saved from the 62.5 Hz transport delay would only be an additional 5 ms. As a general rule of thumb, real-time simulation programs operating above 60 Hz should be sufficient to minimize excess slack CPU time. If additional reductions are necessary, other methods should be employed.

Transport Delays Reduction

Generally, there are two methods available to accomplish additional transport delay reductions. The first is to employ predictor algorithms in the body of the simulation programs. This is not considered an acceptable solution due to the unpredictable nature of the simulations in the FSF. The second method used to reduce the transport delays requires the replacement of existing equipment with faster equipment. The Advanced Computer Generated Image (ACGI) system, scheduled for delivery in August 1994, will reduce the transport delay to the out-the-window scene by about 25 ms. The TSRV is being upgraded with raster monitors and SGI Onyx systems to drive the cockpit instrument information. This will reduce the transport delay for the TSRV HDD by approximately 30 ms.

Conclusions

The transport delay measured for the various simulation components was consistent from program to program. The average transport delay for a simulator is one-half the programs update rate plus the time to calculate the math models next state and the delay due to the output hardware. A program that operates at 31.25 Hz will exhibit average transport delays from 100 to 115 ms to the CGI and from 115 to 140 ms to the CRDS. Further improvements can be made by operating at faster update rates, upgrading the simulator hardware, or improving the display update rates.

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